

**Cleanroom of the Future:  
An Assessment of HVAC Energy Savings Potential  
In a Semiconductor Industry Facility**

**John Busch  
Environmental Energy Technologies Division  
Lawrence Berkeley National Laboratory  
Berkeley, CA 94720**

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## **INTRODUCTION**

Cleanroom facilities in the United States are predicted to grow fourfold by the year 2015, from an estimated floor area of 44 million to 180 million square feet. Depending on air purity requirements, energy intensities in cleanrooms are 10 to 100 times higher than those found in ordinary office environments. While over 30 different industry segments utilize cleanrooms, 70% of U.S. cleanroom floor space is in the semiconductor and other electronic components, pharmaceutical, and biotechnology industries. These latter high-technology industries tend to operate the most energy-intensive cleanrooms due to high standards of cleanliness. Together, these factors portend significant energy demands from cleanrooms.

These high-tech industries are prominent in California as key drivers of the state's economy and as energy consumers. Fourteen percent of U.S. cleanroom floorspace is located in California, with an even large share of 20%-30% of the cleanest, most energy-intensive spaces. Current electricity demand from cleanrooms in California is estimated at 1,200 MW and 5,000 GWh per year (Mills et al, 1996).

Patterns of energy use in cleanroom facilities are not well established. Indeed, efforts are just beginning to benchmark energy consumption in semiconductor cleanrooms, notably by SEMATECH. In many semiconductor industry cleanrooms, half or more of the energy consumed in the facilities is for the heating, ventilating, and air-conditioning systems (HVAC) while most of the rest is for the processes.

The technical opportunities for saving energy in cleanrooms have not been comprehensively studied and are not well documented. Anecdotal estimates of energy savings potential in HVAC consumption are somewhere in the range of 30-80%. Potential savings also exist in production tools used in processes in cleanrooms, although due to the specialized proprietary nature of the technologies used, these are even less well understood than those for HVAC. Cleanroom HVAC systems are based on generally the same technologies as used in other building types. This study exclusively treats HVAC energy savings opportunities and does not address those in production tools.

In an earlier report looking at all California laboratory type facilities (Mills et al, 1996), it was estimated that 80% of the HVAC energy used in all types of cleanrooms—from the dairy industry to the electronics industry and from Class 1 to Class 100,000—could be saved over that of typical practice. This estimate was a “ballpark” figure based on engineering judgement of the authors. In this study we aim to develop a more robust estimate of maximum technical HVAC energy savings potential in California cleanrooms. The intent of this study is to develop a transparent estimate of technical savings potential, documenting all assumptions going into the analysis and utilizing generally accepted analysis techniques. A transparent estimate of savings potential in cleanrooms gives energy policy makers, energy industry stakeholders, and cleanroom industry decision makers in California valuable information regarding where to devote future resources. The results will be presented as a point estimate. Clearly, one could investigate many permutations and sensitivities in the analysis, but those are beyond the scope of this study.

## **METHODOLOGY**

In a nutshell, the approach we followed was to define a typical California cleanroom, define a set of energy efficiency improvements on the typical design, simulate the performance of the typical and efficient designs using a building energy analysis model, and compare the resultant energy use differences between them. Experts from the cleanroom industry involved in HVAC system design and energy analysis were enlisted to assist in defining the profiles for typical and energy efficient cleanroom designs. As the goal was to estimate the technical energy savings potential, many currently available energy efficiency measures in HVAC technology were considered. The economic energy savings potential, where only those energy efficiency measures passing some cost-effectiveness threshold are included, is beyond the scope of this study.

The process of analyzing savings potential went as follows:

1. Base case cleanroom defined based on typical characteristics published in literature.
2. Cleanroom experts review base case cleanroom profile and suggest modifications to profile to modernize it in line with their experience
3. Recommendations synthesized into revised base case cleanroom profile
4. Cleanroom experts suggest HVAC energy efficiency improvements to the base case profile to achieve energy savings with current technology
5. Recommendations synthesized into an energy efficient cleanroom profile
6. Energy performance of typical and efficient designs simulated
7. Compare results

### **Base Case**

Due to the importance of the semiconductor industry in California's economy, the large amount of U.S. Class 1 and 10 cleanroom floor space located in California (30%) and their high energy intensities, we defined the base case as a Class 1 semiconductor cleanroom facility located in Silicon Valley. The base case profile is based on previous analyses by Naughton (1990a and 1990b), modified to reflect current practice.

It is a 10,000 ft<sup>2</sup> facility operated continuously (i.e., 24 hours per day, 7 days per week). Key aspects of the base case are shown in Table 1.

### **Energy Efficient Cleanroom**

The energy efficiency measures applied to the base case cleanroom design are shown in Table 2. The table describes only the changes made to the base case. Improvements were made only to the HVAC system, leaving the cleanroom architecture and processes unchanged.

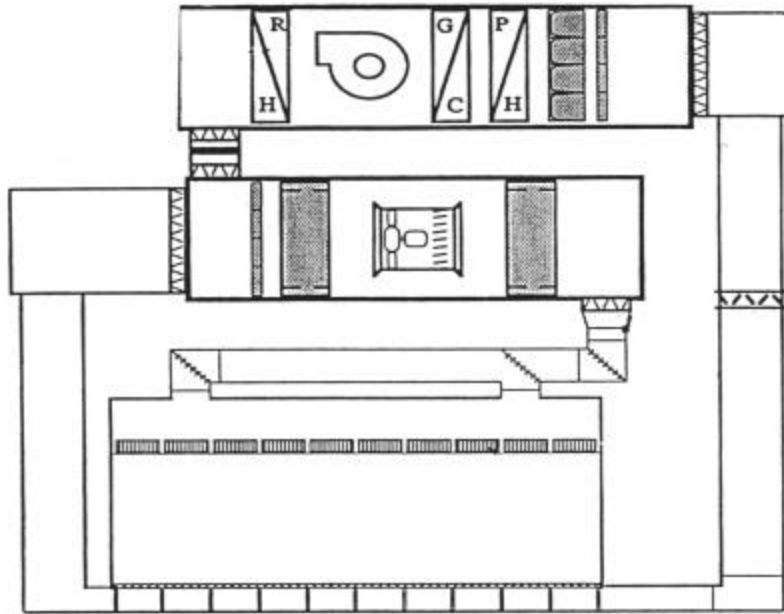
**Table 1. Energy Characteristics of Base Case Cleanroom**

Envelope Design	Cleanroom is thermally isolated from exterior climatic conditions because it is contained within a larger building with no windows and surrounded by conditioned air (modeled as adiabatic walls).
Interior Conditions	<ul style="list-style-type: none"> <li>• Temperature setpoint 68 F <math>\pm</math> 1 F</li> <li>• RH 40% <math>\pm</math> 1%</li> <li>• Lighting system F40 fluorescent lamps, magnetic ballasts with installed power density = 5 W/ft<sup>2</sup></li> <li>• Sensible internal heat gains from equipment (e.g., floor tools) = 50 W/ft<sup>2</sup></li> </ul>
HVAC Air-Side Design	<ul style="list-style-type: none"> <li>• Separate air handling units for recirculation with no conditioning apparatus and AHUs for make-up and return air with sensible and dehumidifying coils (Figure 1)</li> <li>• Unidirectional vertical laminar airflow with 70 fpm air velocity</li> <li>• Exhaust air requirements 4 cfm/ft<sup>2</sup></li> <li>• Make-up air 125% of exhaust air requirements for pressurization (i.e. 5 cfm/ft<sup>2</sup>) (Brown 1990)</li> <li>• HEPA filter system</li> <li>• Silencers used to dampen fan noise</li> <li>• Constant volume fan control</li> <li>• Static pressure of 6" w.c. on makeup air unit and 4" w.c. on recirculation air unit</li> <li>• Make-up air unit 170,000 cfm (120,000 of return air plus 50,000 cfm of makeup air)</li> <li>• Recirculation air unit capacity 700,000 cfm</li> <li>• Fan efficiency 65%</li> <li>• Fan motor efficiency 85%</li> <li>• Fan drive efficiency 95%</li> </ul>
HVAC Water-Side Design	<ul style="list-style-type: none"> <li>• Centrifugal chiller efficiency 0.65 kW/ton</li> <li>• Chilled water supply temperature 41F</li> <li>• Cooling towers on condensers with two-speed capacity control</li> <li>• Gas-fired hot-water boiler with atmospheric burner, efficiency 80%</li> </ul>

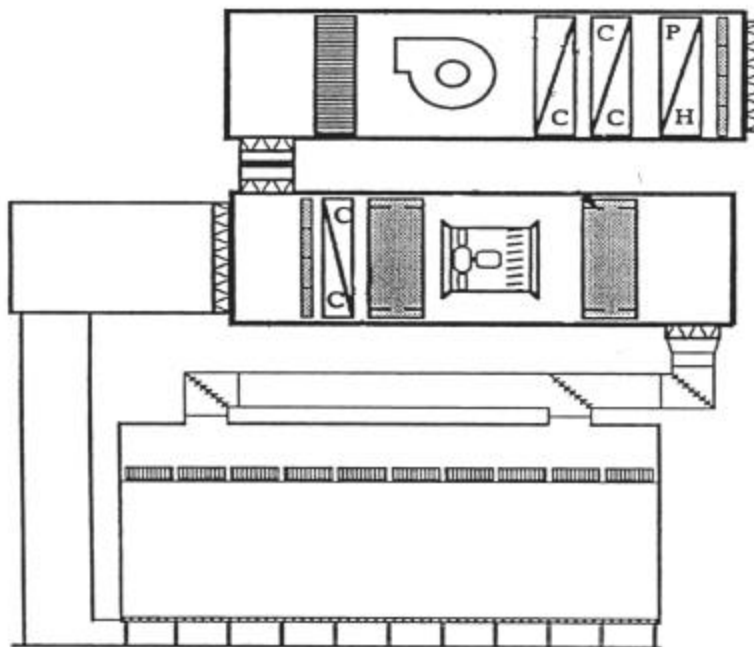
**Table 2. Measures in Energy Efficient Cleanroom**

Interior Conditions	<ul style="list-style-type: none"> <li>• Temperature setpoint 70 F <math>\pm</math> 2 F</li> <li>• Relative humidity 45% <math>\pm</math> 3%</li> </ul>
HVAC Air-Side Design	<ul style="list-style-type: none"> <li>• Recirculation AHUs with sensible conditioning apparatus and make-up AHUs with sensible and dehumidifying coils (Figure 2).</li> <li>• Air velocity 65 fpm</li> <li>• Exhaust air requirements 4.5 cfm/ft<sup>2</sup> (based on 1997 UBC/UFC increased minimum ventilation rate to 4 from 1 cfm/ft<sup>2</sup>)</li> <li>• Fewer or no silencers to dampen fan noise</li> <li>• Static pressure of 4" w.c. on makeup air units and 2" w.c. on recirculation air units</li> <li>• Make-up air quantity 45,000 cfm (40,000 cfm exhaust plus 5,000 cfm pressurization air)</li> <li>• Recirculation air quantity 650,000 cfm</li> <li>• Fan efficiency 85%</li> <li>• Fan motor efficiency 94%</li> </ul>
HVAC Water-Side Design	<ul style="list-style-type: none"> <li>• Centrifugal chiller efficiency 0.5 kW/ton</li> <li>• Chilled water supply temperature 42 F</li> <li>• Cooling towers (VSD capacity control, efficiency 0.013 bhp/ton)</li> <li>• Water-side economizer control</li> <li>• Modular pulse combustion gas hot water boilers with power burners, efficiency 95%</li> <li>• Pump motor efficiency 94%</li> <li>• Pump VSD control</li> </ul>

Figures 1 and 2 are schematic drawings of the base case and energy efficient case HVAC system configurations, respectively, from Naughton (1990b).



**Figure 1. Base case cleanroom HVAC system configuration.**



**Figure 2. Energy efficient case cleanroom HVAC system configuration.**

## DOE-2

We used the DOE-2.1E building energy simulation program to estimate the energy performance of different cleanroom configurations. DOE-2 is widely recognized as a state-of-the-art tool for simulating the energy performance of buildings described in terms of their geometry, materials, equipment, occupancy, and operation, in response to weather. The program solves, on an hour-by-hour basis, the mathematical relations governing the thermodynamic behavior of a building. It does this in sequential steps through four modules: LOADS, SYSTEMS, PLANT, and ECONOMICS (although we did not use the latter module in this study). In the LOADS module, based on user input describing building surfaces, enclosed spaces, internal usage, and schedules, the instantaneous heating and cooling loads are calculated and then modified to incorporate dynamic effects of thermal mass through the use of weighting factors. The SYSTEMS module calculates the heat extraction or addition of the coils and ventilation schemes from a large menu of system types and operation parameters. The PLANT module calculates the fuel and electricity requirements to operate primary heating and cooling equipment, and their auxiliaries (such as pumps) (BESG, 1985).

Modeling the base case and energy efficient cleanrooms with DOE-2 was not a straightforward exercise. The main reason is that the HVAC systems shown in Figures 1 and 2, while typical for cleanrooms are not typical for most buildings. DOE-2 users cannot specify more than one HVAC system serving a single zone. Our solution to this limitation was to place one of the systems in the service of a “dummy” zone, one cubic foot in volume, with essentially no loads, and specify interconnections between the two systems through existing DOE-2 commands. We find that this trick does not introduce any bias or inaccuracy in the simulation. Details of the modeling strategy and DOE-2 inputs are described in the appendix.

## RESULTS

### Base Case

Electricity makes up 93% of total site energy<sup>1</sup> consumed in the base case facility. Sixty-seven percent of electricity in the base case is consumed by the HVAC system. Figure 3 shows the end-use breakdown of electricity consumption by the HVAC system. In the base case, fans consume nearly half (46%) the electricity in the facility, followed by process loads (30%), cooling (18%), lighting (3%), and pumps and cooling towers (2% each) while heating is negligible. Fans use two-thirds and cooling uses a quarter of electricity consumed by the HVAC system, while the tower and pumps use 3% each. Figure 4 shows the HVAC end-use breakdown for total energy (i.e., including gas and electricity). Heating figures more prominently in the total energy picture, rising to 7% overall and 10% of HVAC energy. The energy intensities of the HVAC system are 1000 kWh/ft<sup>2</sup>/year and 4 GJ/ft<sup>2</sup>/year.

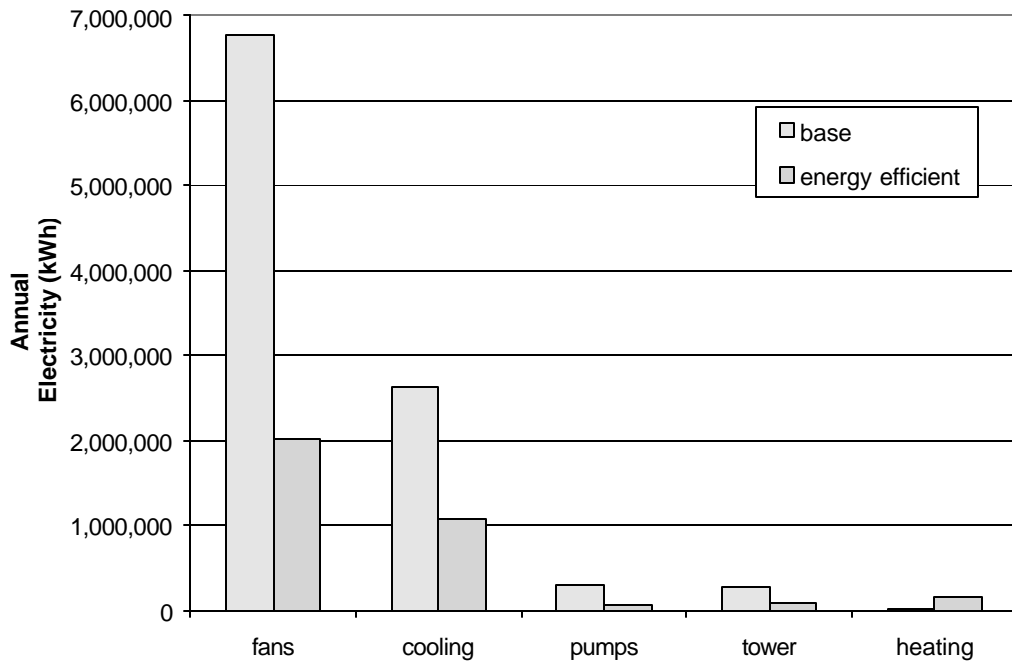
### Energy Efficient Cleanroom

Figure 5 displays percentage savings achieved in the energy efficient cleanroom in total, for the HVAC system, and for each end-use for electricity and total energy. Overall, electricity savings are 45% and energy savings are 27%. For the HVAC system, electricity savings are 66% and energy savings are 39%. With the exception of heating, the savings of each HVAC end-use are 60% to 80%. Monthly peak demand, shown in Figure 6, becomes more stable throughout the year in the energy efficient case and drops by 53%.

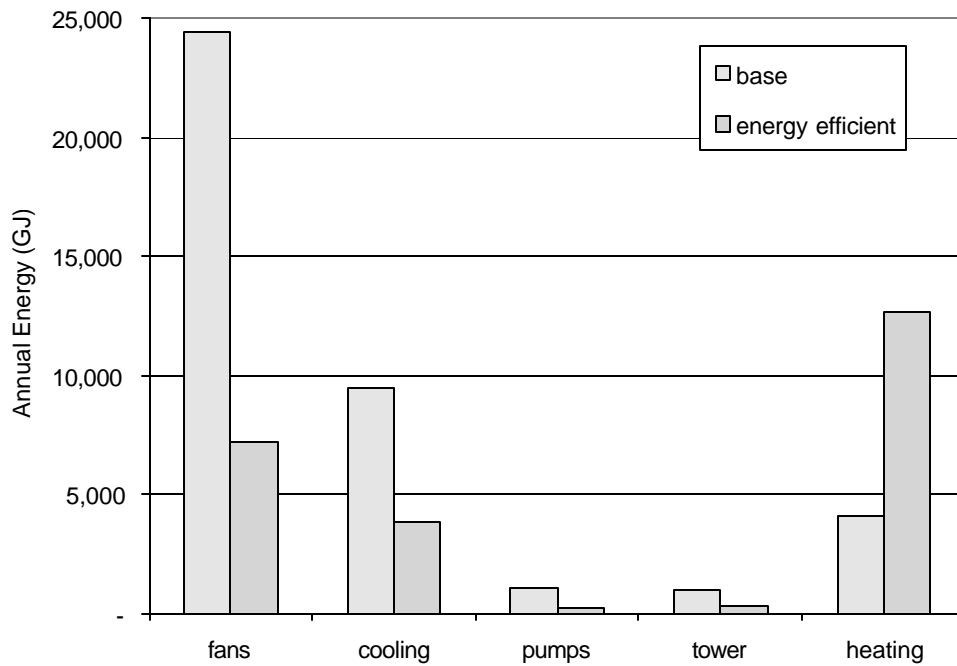
These savings are achieved through better technology and improved overall system design and utilization. While the heating system also employs efficient technology, the changes in system configuration and other end-uses result in significant increases in heating energy consumption. Nearly three-quarters of the electricity savings come from the fans, and a quarter from cooling. Whereas, slightly over half the total

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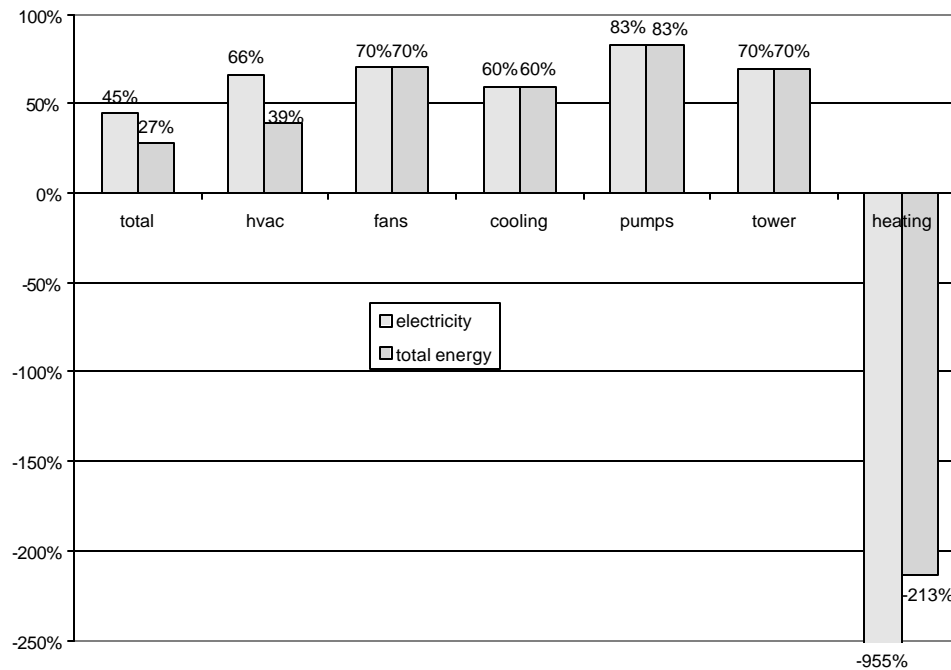
<sup>1</sup> Throughout the paper, all references to energy are on a site basis, not primary or resource basis.



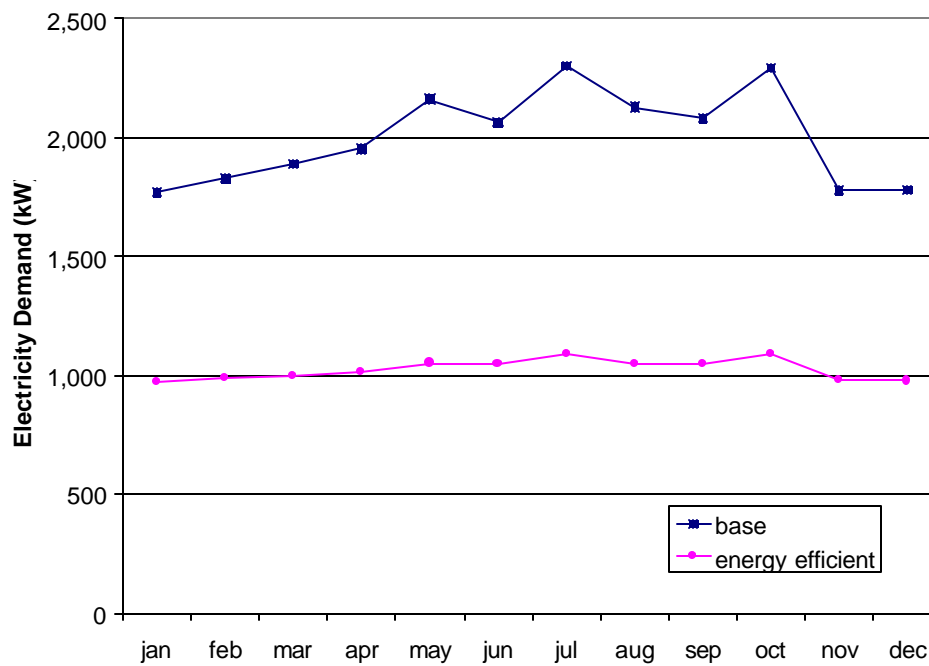
**Figure 3. End use breakdown of annual electricity consumption for two cleanroom cases.**



**Figure 4. End use breakdown of annual energy consumption for two cleanroom cases.**



**Figure 5. Savings in energy efficient cleanroom by component for electricity and total energy.**



**Figure 6. Monthly peak demand for two cleanroom cases.**



energy savings come from the fans (net of lost waste heating “penalty”), a third from cooling, and 10% from towers and pumps.

Electricity’s share of total energy consumption falls to 71% and natural gas’s rises to 29% in the energy efficient cleanroom. Overall, HVAC consumption falls to 41% of total electricity and 58% of total energy. Fans use 25% of total electricity, while cooling uses 13%, and heating, towers, and pumps use 1-2% each. In terms of HVAC electricity proportions, there are only minor shifts from the base case. Figure 3 shows how HVAC end-use electricity consumption shifts in the energy efficient cleanroom as compared to the base case, including the slight increase in heating electricity for the boiler power burner. The change from the base case in terms of total energy end-use breakdown, shown in Figure 4, is much more dramatic. Heating becomes the largest energy end-use at 31%, followed by fans at 17% and cooling at 9%. In terms of HVAC energy, heating constitutes half, fans a third, and cooling a sixth share. The energy intensities of the HVAC system are 336 kWh/ft<sup>2</sup>/year and 2.4 GJ/ft<sup>2</sup>/year.

The shift in fuel shares is largely because of changes in fan energy use. Fan capacity is reduced because of lower airflows and coupled with fan efficiency improvements, electricity consumption is reduced, but so is the waste heat added to the air for “free” that has been made up for by increased load on the heating system. HVAC also claims a smaller share of the electricity budget due to process loads remaining unchanged.

## CONCLUSIONS

Cleanrooms present large opportunities for saving energy and reducing electricity demand. Our results suggest that very significant energy savings in cleanrooms can result from integrating off-the-shelf technologies and mainstream HVAC system design concepts and optimizing the design for energy efficiency. Not unexpectedly, airflow design emerges as the key element in any strategy to capture savings in cleanrooms. The trend towards the use of packaged fan and filter units with their generally lower efficiencies complicates any such strategy.

This technical potential study represents a first step in uncovering the energy efficiency opportunities in cleanrooms. The results cannot be generalized to all types of cleanrooms. A more comprehensive study of the technical energy efficiency opportunities would look at different types of cleanrooms, more technologies, system configurations, and sensitivities to key parameters. In addition, economic potential and market achievable potential needs to be examined.

For the “cleanroom of the future” to become the cleanroom of the present, daunting but not insurmountable market barriers will have to be overcome. The case of the microelectronics industry illustrates why energy efficient technologies in cleanrooms have largely not been adopted. First, new manufacturing facilities must be brought into production on an extremely fast track due to short product cycles and intensely competitive market pressures. This compressed schedule cuts into time allocated for design of facility and process engineering, with the result that energy efficiency improvements get little attention. Second, high value for the product puts a premium on reliability of overall production facility in terms of minimizing production line downtime and defects due to contamination. This promotes extreme conservatism in cleanroom design and operation. Any strategy for promoting energy efficiency in cleanrooms must address these concerns.

In practical terms, cleanroom designers, decision-makers, and analysts might become more interested in cleanroom energy efficiency if a calibrated energy simulation tool were available to predict and test the energy and financial implications of various cleanroom HVAC design choices. Specifically, it is important to be able to simulate more than one system serving a single zone and accurately model fan energy use at extremely high flow rates. Commercially available building energy analysis tools have limitations in these areas, forcing the user to resort to creative “work arounds” as we did here. Perhaps

some cleanroom design firms possess models developed in-house with these capabilities, but they are proprietary products for internal use only. Even if any of these models were licensed for outside use, they would need to undergo scrutiny by the engineering community and validated before general reliance could be placed on the results they produce.

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